

# Sussex Research Online

## The local star formation rate and radio luminosity density

Article (Published Version)

Serjeant, Stephen, Gruppioni, Carlotta and Oliver, Seb (2002) The local star formation rate and radio luminosity density. *Monthly Notices of the Royal Astronomical Society*, 330 (3). pp. 621-624. ISSN 0035-8711

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/28156/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

### Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

# The local star formation rate and radio luminosity density

Stephen Serjeant,<sup>1,4</sup>★ Carlotta Gruppioni<sup>2,4</sup> and Seb Oliver<sup>3,4</sup>

<sup>1</sup>*Unit for Space Sciences and Astrophysics, School of Physical Sciences, University of Kent, Canterbury, Kent CT2 7NR*

<sup>2</sup>*Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy*

<sup>3</sup>*Astronomy Centre, CPES, University of Sussex, Falmer, Brighton BN1 9QJ*

<sup>4</sup>*Astrophysics Group, Blackett Laboratory, Imperial College of Science Technology and Medicine, Prince Consort Road, London SW7 2BW*

Accepted 2001 October 26. Received 2001 October 26; in original form 2001 June 19

## ABSTRACT

We present a new determination of the local volume-averaged star formation rate from the 1.4-GHz luminosity function of star forming galaxies. Our sample, taken from the  $B \leq 12$  Revised Shapley–Arnes catalogue (231 normal spiral galaxies over an effective area of  $7.1$  sr) has  $\simeq 100$  per cent complete radio detections and is insensitive to dust obscuration and cirrus contamination. After removal of known active galaxies, the best-fitting Schechter function has a faint-end slope of  $-1.27 \pm 0.07$  in agreement with the local H $\alpha$  luminosity function, characteristic luminosity  $L_* = (2.6 \pm 0.7) \times 10^{22}$  W Hz $^{-1}$  and density  $\phi_* = (4.8 \pm 1.1) \times 10^{-4}$  Mpc $^{-3}$ . The inferred local radio luminosity density of  $(1.73 \pm 0.37 \pm 0.03) \times 10^{19}$  W Hz $^{-1}$  Mpc $^{-3}$  (Poisson noise, large-scale structure fluctuations) implies a volume-averaged star formation rate  $\sim 2$  times larger than the Gallego et al. H $\alpha$  estimate, i.e.  $\rho_{1.4\text{GHz}} = (2.10 \pm 0.45 \pm 0.04) \times 10^{-2}$  M $_{\odot}$  yr $^{-1}$  Mpc $^{-3}$  for a Salpeter initial mass function from  $0.1$ – $125$  M $_{\odot}$  and Hubble constant of  $50$  km s $^{-1}$  Mpc $^{-1}$ . We demonstrate that the Balmer decrement is a highly unreliable extinction estimator, and argue that optical–ultraviolet (UV) star formation rates (SFRs) are easily underestimated, particularly at high redshift.

**Key words:** surveys – galaxies: evolution – galaxies: formation – galaxies: Seyfert – galaxies: starburst – infrared: galaxies.

## 1 INTRODUCTION

Some of the most ambitious and widely cited extragalactic observations in recent years have been the constraints made on the star formation history of the Universe. Madau et al. (1996) used the ultraviolet luminosity density as a tracer of the comoving star formation rate (SFR), and by combining  $z \gtrsim 3$  Lyman dropout surveys (Steidel et al. 1998) with the  $0.1 < z < 1$  Canada–France Redshift Survey (CFRS; Lilly et al. 1996) they inferred a  $z \sim 1.5$  peak and subsequent redshift cut-off in the SFR. If correct this is a major result, implying an empirical determination of the dominant epoch of metal production in the Universe [also suggestively close to the peak in quasi-stellar object (QSO) number density] which can be compared directly with hierarchical models of galaxy formation (Baugh et al. 1998). The dereddened CFRS ultraviolet SFR quoted in Lilly et al. (1996) appears to asymptote to the local (dereddened) H $\alpha$  estimate from Gallego et al. (1995). However, ultraviolet (UV) estimates are very sensitive to dust obscuration, with reddening corrections ranging from factors of the order of 2 (Madau et al. 1996) to 10 (Meurer, Heckman & Calzetti 1999). Indeed there have been several claims that less reddening-dependent measures yield substantially higher star formation rates:

for example, submillimetre galaxy surveys both behind lensing clusters (e.g. Blain et al. 1999a,b; Ivison et al. 2000) and in the field (e.g. Hughes et al. 1998; Barger, Cowie & Sanders 1999a; Barger et al. 1999b; Lilly et al. 1999a,b; Eales et al. 1999, 2000; Peacock et al. 2000; Serjeant et al. 2001; Fox et al., in preparation; Scott et al., in preparation) find star formation rates at  $z > 3$  comparable to dereddened UV-selected samples, but the galaxy populations which appear to comprise the submillimetre point sources overlap little with the UV-selected star forming population; interstellar object (ISO) observations of the *Hubble Deep Fields* at  $7$  and  $15\mu\text{m}$  (Rowan-Robinson et al. 1997; Oliver et al., in preparation) find systematically higher star formation rates than inferred at  $z \sim 0.5$ – $1$  in the optical; the H $\alpha$  luminosity density in the CFRS (Tresse & Maddox 1998) implies a  $z \sim 0.3$  star formation rate  $2$ – $3$  times higher than that inferred from dereddened ultraviolet estimates; and the evolving radio luminosity density is also consistent with comparable amounts of star formation from UV samples and inaccessible to UV samples (Haarsma et al. 2000).

In this paper we will show that the local H $\alpha$  star formation rate is itself also a significant underestimation, by comparing it with the local radio luminosity density of star forming galaxies. This paper is structured as follows. In Section 2 we present the sample used in this paper, and corresponding selection criteria. Section 3 presents

★E-mail: s.serjeant@ukc.ac.uk

a calculation of the local radio luminosity function and luminosity density. Implications of these results are discussed in Section 4. We assume a Hubble constant of  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0.5$ .

## 2 SAMPLE DEFINITION

Unlike the far-infrared (far-IR), H $\alpha$  and UV, the radio luminosity density traces both obscured and unobscured star formation, as well as being free of cirrus contamination that affects far-IR estimates at faint luminosities (Condon, Anderson & Helou 1991). At low radio frequencies ( $\sim 1 \text{ GHz}$ ) the luminosity is dominated by non-thermal emission, plausibly from cosmic ray electrons accelerated by supernovae, which can be calibrated to the recent star formation rate using the supernova rate in the Galaxy (Condon 1992; Section 3). The low-frequency radio luminosity density is therefore an ideal estimator of the local volume-averaged star formation rate.

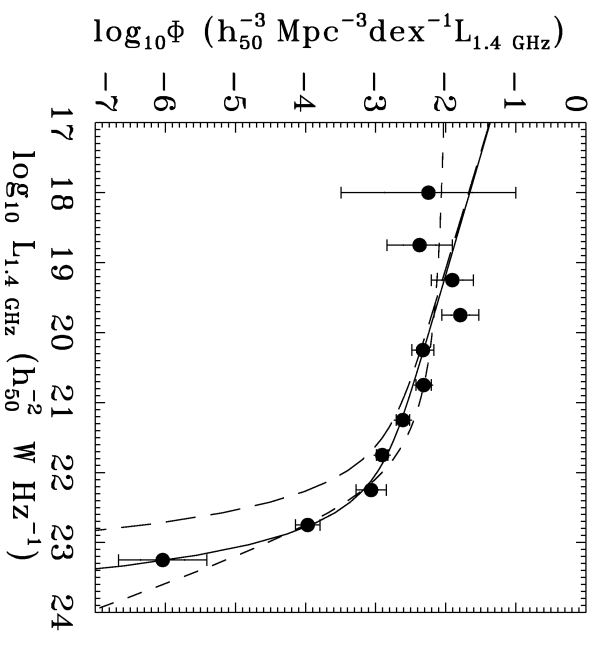
The  $B \leq 12$  spiral galaxies in the Revised Shapley-Ames catalogue were mapped at 1.4 GHz by Condon (1987) with the Very Large Array (VLA) to limiting flux densities of (typically)  $0.1 - 0.5 \text{ mJy}$ , obtaining detections of virtually 100 per cent of the sample. The survey spans a sufficiently large cosmological volume for large-scale structure density fluctuations to be negligible in comparison with the shot noise on the luminosity density and overall number density (Condon 1989; Oliver, Gruppioni & Serjeant 1998); using the Peacock & Dodds (1994) power spectrum we estimate density fluctuations of less than 2 per cent on the scale of the survey, which agrees with the uniformity of the  $\langle V/V_{\text{max}} \rangle$  statistic derived by Condon (1989). Nevertheless, as a precaution the Local Group is excluded by eliminating the 10 galaxies within 1.7 Mpc, and the Virgo Cluster is excluded by removing the 27 galaxies within  $10^\circ$  of the cluster centre. These exclusions leave a sample of 267 spiral galaxies. With the correction for galactic extinction, the resulting survey has an effective areal coverage of  $\approx 7.1 \text{ sr}$  (Condon 1989).

The contribution of active galactic nuclei (AGN) could potentially introduce a significant systematic error into estimates of the radio luminosity density; indeed, Ho, Filippenko & Sargent (1997) have shown that at least 50 per cent of spiral galaxies show some evidence for activity when a very low detection level is used and the stellar absorption from the host galaxy is properly corrected. However the appropriate question is not whether an active nuclei are present, but whether the nuclei contribute significantly to the low-frequency radio fluxes. Condon et al. (1991) found that removing the Seyfert galaxies listed in the Véron-Cetty & Véron (1993) catalogue from the IRAS Bright Galaxy Sample and RSA samples, also eliminated the outliers in the radio-far-IR correlation. Although such AGN segregation is somewhat arbitrary, this is strong circumstantial evidence that the remaining galaxies represent a more homogeneous population. We can reasonably interpret the remaining galaxies to be those in which the radio and far-IR are dominated by star formation. We therefore eliminated the 36 galaxies listed as Seyferts in the Véron-Cetty & Véron (1993) catalogue, differing somewhat from the approach of Condon (1989) (with a non-negligible effect around the break of the luminosity function; Section 3). The exclusion of AGN neglects any contributions from circumnuclear star formation in these objects, and any star formation in ellipticals is also explicitly excluded, so the luminosity density from star formation derived in this paper should strictly speaking be treated as a lower limit. Furthermore, it is important to note that none of the SFR from UV estimates from the CFRS, Lyman drop-out samples and

the H $\alpha$  luminosity density of Tresse & Maddox (1998) (and indeed most SFR studies) excludes any narrow-line AGN contribution.

## 3 THE RADIO LUMINOSITY FUNCTION

In Fig. 1 we plot the  $1/V_{\text{max}}$  estimate of the radio luminosity function (Schmidt 1968) for this sample. Accessible volumes were limited on one side by the Local Group redshift limit (Section 2), and on the other by the maximum redshift at which an otherwise identical galaxy would be observable with these flux limits. (In practice the optical limit dominates the selection.) As noted in Oliver et al. (1998), the presence of two flux limits (optical and radio) does not affect the  $1/V_{\text{max}}$  estimate of the luminosity function, as long as (i) the minimum  $z_{\text{max}}$  redshift of the two flux limits is used, and (ii) the luminosity function is corrected for any parts of the (radio, optical) luminosity plane which are inaccessible at all redshifts. In this case, the latter consideration is negligible.



**Figure 1.** Local 1.4-GHz radio luminosity function of Revised Shapley-Ames spiral galaxies, with the known AGN from Véron-Cetty & Véron (1993) catalogue excluded. Errors are the  $\Sigma 1/V_{\text{max}} \pm \sqrt{\Sigma 1/V_{\text{max}}^2}$  range in the case of  $>1$  galaxy in the bin; for bins with a single galaxy the errors represent  $\pm 1\sigma$  limits on the appropriate Poisson distribution mean. The full line shows the Schechter function fit described in the text, and the short dashed line shows the original Condon (1989) luminosity function. The long dashed line shows the best-fitting H $\alpha$  luminosity function of Gallego et al. (1995), scaled using equations (2) and (3).

**Table 1.** Local 1.4-GHz luminosity function parameters:  $\phi(L) dL = \phi_*(L/L_*)^\alpha \exp(-L/L_*) d(L/L_*) \text{ Mpc}^{-3}$ . The large-scale structure density fluctuations are estimated to be around 2 per cent on the scale of the survey, and are not incorporated into the tabulated errors. We assume a Hubble constant of  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

Parameter	Minimum $\chi^2$ value	$\pm 1\sigma$ range
$\phi_*$ ( $\text{Mpc}^{-3}$ )	$4.9 \times 10^{-4}$	$(3.7 - 5.9) \times 10^{-4}$
$L_*$ ( $\text{W Hz}^{-1}$ )	$2.8 \times 10^{22}$	$(1.9 - 3.3) \times 10^{22}$
$-\alpha$	1.29	1.21 - 1.35
$L_* \phi_* (2 + \alpha)$ ( $\text{W Hz}^{-1} \text{ Mpc}^{-3}$ )	$1.73 \times 10^{19}$	$(1.35 - 2.08) \times 10^{19}$

Bins with only one galaxy have errors corresponding to  $1\sigma$  limits on the mean of the appropriate Poisson distribution; errors are  $\sqrt{2}/V_{\max}^2$  otherwise. To avoid two consecutive single-membered bins, the two faintest bins were combined to make a single bin at  $10^{18\pm0.5}h_{90}^{-2}\text{ W Hz}^{-1}$ . We obtained a best-fitting solution with a reduced  $\chi^2$  of 0.8, tabulated in Table 1. By comparison, the original Condon (1989) luminosity function has  $\chi^2_{\nu} = 5.5$  with this data set, due to the inclusion of several AGN in their fit. Errors on each parameter were obtained treating the other parameters as fixed.

We have already argued that the  $\phi_*$  is insensitive to density fluctuations in this sample, though it remains to be shown that  $L_*$ ,  $\alpha$  and the luminosity density are unaffected. In order to demonstrate this, we compared the observed radio luminosity distribution with that expected for the model luminosity function, using a fit to the radio–optical correlation given in Condon (1987). This has the advantage of being independent of the local density distribution. Using the Kolmogorov–Smirnov statistic on the luminosity histograms to define a likelihood statistic, we find that our minimum  $\chi^2$  parameters are an excellent fit to the luminosity distribution.

The faint-end slope is in good agreement with that obtained for the local H $\alpha$  luminosity function by Gallego et al. (1995). Note that we should not necessarily expect the slope of the radio luminosity function, which is a measure of the recent star formation rate, to match that of e.g. the  $B$ -band luminosity function, due to the latter having contributions from less recent star formation. It is also important to note that our constraint on the faint-end slope is dominated by objects with luminosities  $(3 \times 10^{-3} \sim 0.3) \times L_*$ , and is affected little by the exclusion of fainter bins. The data do not fit a flat slope throughout  $(3 \times 10^{-3} \sim 0.3) \times L_*$  (though in the faintest bins a flattening cannot be excluded). This ‘useful’ faint-end luminosity range is  $\sim 1$  dex deeper relative to  $L_*$  than that of Gallego et al. (1995), and comparable to e.g. that of Tresse & Maddox (1998). The total luminosity density of a Schechter luminosity function is given by  $\phi_* L_* (2 + \alpha)$ , but the errors in these parameters are highly correlated. We therefore explored the parameter space to find the regions where  $\text{Pr}(\chi^2_0) < 0.68$ , and hence determined the  $\pm 1\sigma$  luminosity density range, also listed in Table 1.

At these frequencies the radio luminosity is dominated by non-thermal emission from relativistic electrons (Condon 1992) accelerated by supernovae from massive ( $M \geq 5 M_{\odot}$ ) stars. The lifetimes of such stars are only  $\sim 10^7$  yr, so the low-frequency radio emission should be proportional to the recent star formation rate. Following Condon (1992) and Condon & Yin (1990), this can be calibrated using the Galactic non-thermal radio luminosity, obtaining

$$\text{SFR}(100 \geq M/M_{\odot} \geq 5) = \frac{L_{1.4\text{GHz}}[\text{W Hz}^{-1}]}{5.3 \times 10^{21}(\nu/\text{GHz})^{-\alpha}} M_{\odot} \text{ yr}^{-1} \quad (1)$$

where  $\nu$  is the frequency and  $\alpha$  is the non-thermal radio spectral index ( $\alpha = -\text{d} \log S_{\nu} / \text{d} \log \nu \approx 0.8$ ). Assuming a Salpeter initial mass function (IMF;  $\eta(M) \propto M^{-2.35}$ ) we can correct to  $0.1\text{--}125 M_{\odot}$  if we divide by  $(100^{-0.35} - 5^{-0.35})/(125^{-0.35} - 0.1^{-0.35}) \approx 0.18$ , and can correct from 1 to  $1.4\text{ GHz}$  with the factor of  $1.4^{-0.8}$ . The non-thermal contribution at  $1\text{ GHz}$  is  $\sim 90$  per cent of the total luminosity (Condon 1992), so we therefore obtain for the star formation rate

$$\text{SFR}(125 \geq M/M_{\odot} \geq 0.1) = \frac{L_{1.4\text{GHz}}[\text{W Hz}^{-1}]}{8.2 \times 10^{20}} M_{\odot} \text{ yr}^{-1} \quad (2)$$

where  $L_{1.4\text{GHz}}$  is the total monochromatic luminosity at that wavelength. Our observed luminosity density (Table 1) therefore

corresponds to a volume-averaged SFR of  $(2.10 \pm 0.45) \times 10^{-2} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ . The SFR is dominated by objects around  $L_*$ , peaking at  $\sim 0.7 L_*$  which corresponds to around  $25 M_{\odot} \text{ yr}^{-1}$ . We can compare this estimate with that obtained from the local H $\alpha$  luminosity density quoted by Gallego et al. (1995). For our adopted IMF, Madau, Pozzetti & Dickinson (1998) quote a conversion of

$$\text{SFR}(125 \geq M/M_{\odot} \geq 0.1) = \frac{L_{\text{H}\alpha}[\text{W}]}{1.41 \times 10^{34}} M_{\odot} \text{ yr}^{-1} \quad (3)$$

for unreddened (i.e. dust-free) H $\alpha$  luminosity densities, Gallego et al. dereddened their H $\alpha$  fluxes using Balmer decrements, and their resulting luminosity density corresponds to a volume-averaged SFR of  $(8.8 \pm 0.1) \times 10^{-3} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ , about a factor of 2 lower than our radio estimate. We will discuss the reasons for the Balmer decrement failing in Section 4; a similar systematic offset was seen in the (albeit inhomogeneous) samples of Cram et al. (1998), whose H $\alpha$ -derived star formation rates were a few to 10 times lower than radio estimates, with the more luminous systems showing the larger offset. Indeed our luminosity function is in good agreement with that of Gallego et al. at the faint end (Fig. 1), but shows a consistently higher number density around and above our  $L_*$  where the contribution to the luminosity density is significant.

#### 4 DISCUSSION

We have found that even the de-reddened H $\alpha$  luminosity density underestimates the local volume-averaged star formation rate by a factor of  $\sim 2$ . (Strictly speaking our radio SFR is a lower limit, as it excludes the SFR from irregulars and ellipticals.) However, this does not imply that the global SFR is dominated by extreme, highly obscured ultraluminous galaxies – indeed we have found the local luminosity density dominated by only  $\sim 25 M_{\odot} \text{ yr}^{-1}$  systems. Neither does it imply, for instance, that spiral discs are predominantly opaque. It does however require that a significant fraction of star formation occurs in the cores of giant molecular clouds, which must survive destruction from photodissociation and supernova-driven shocks long enough to obscure a significant fraction of the O and B stars.

At faint radio luminosities, where we have suggested the lowest extinction, the radio–far-IR correlation becomes non-linear. This is usually attributed to the increasing cirrus contribution in the far-IR. This contribution can be estimated using the  $B$  magnitudes (Devereux & Eales 1989) but at the cost of a greatly increased scatter in the corrected correlation. However, Condon et al. (1991) showed that this can be avoided by allowing the cirrus contribution to also depend on the radio luminosity – in essence, the cirrus (of whatever temperature) is partly heated by unobscured OB stars. This is thus in perfect accord with our lower extinction at the faint end of the luminosity function.

Conversely, the extinction corrections are significant at around  $L_*$ . One naive interpretation of our high radio SFRs would be to invoke a second, high extinction component to the SFR. However, two components are not necessary. Consider a simple constant-density model where the dust in the star forming regions is well mixed with the H $\alpha$ -emitting gas. Following Kroker et al. (1996) and Thronson et al. (1999), the observed H $\alpha$  flux  $S_0$  of the dusty star forming region is related to the ‘intrinsic’ H $\alpha$  flux  $S_0$  which would be observed in the absence of dust, by

$$S = S_0(1 - e^{-\tau})/\tau \quad (4)$$



where  $\tau \approx 0.7A_V$  is the H $\alpha$  optical depth to the rear of the star forming region. Assuming an extinction correction of  $\approx 1$  mag was applied to the Gallego et al. (1995) SFR (Kennicutt 1983; Tresse & Maddox 1998), our radio SFR implies

$$\frac{S}{S_0} \approx \frac{0.88 \times 10^{-0.4}}{2.1} = 0.167 \quad (5)$$

and hence  $A_V \approx 9$ . (It is important to stress that this is the extinction to the rear of the cloud, and not a ‘typical’ extinction.) The observed H $\beta$  flux can also be derived using  $\pi(H\beta) \approx 1.45\pi(H\alpha)$ . Remarkably, the predicted Balmer decrement in this model would imply only  $A_V \approx 1.1$  in this model if one (wrongly) assumed a simple dust screen, *regardless of the true  $A_V$* , due to the low- $A_V$  regions dominating the observed Balmer line fluxes. This is in excellent agreement with the typical observed Balmer decrements in H $\alpha$  surveys (Kennicutt 1983; Tresse & Maddox 1998). The reddening corrections derived from optical-UV colours will also be underestimates, as the observed spectra are also dominated by the regions with the smallest obscuration. This effect will be strongest at high redshifts, where the rest-frame wavelengths are the shortest. Naïve reddening corrections could therefore easily introduce redshift-dependent biases into the comoving SFR estimates. Even ‘effective’ reddening corrections based on typical starburst optical-UV SEDs (e.g. Heckman et al. 1998) could miss the most highly obscured components unless such SFRs are explicitly normalized to a more isotropic indicator (e.g. Meurer et al. 1997; Cram et al. 1998).

Nevertheless, the prospects for reddening-independent constraints on the comoving SFR at high  $z$  are excellent, due mainly to the fact that the strong far-IR-radio correlation implies the far-IR can also provide unbiased SFR estimates. For example, optical spectroscopy of new surveys conducted with the *Infrared Space Observatory (ISO)*, such as European Large Area *ISO* survey (ELAIS; Oliver et al. 2000), *ISO* observations of the *Hubble Deep Field ISO-HDF*, Serjeant et al. 1997; Rowan-Robinson et al. 1997) and others (e.g. Taniguchi et al. 1997; Lemonon et al. 1998), will shortly probe the SFR to redshifts of  $z \sim 1-2$ . Unlike the dereddened UV and H $\alpha$  estimates, these mid-IR and far-IR selected samples are sensitive to star formation in even the most obscured giant molecular clouds, with in some cases independent consistency checks available from low-frequency sub-mm radio follow-up observations (e.g. Ciliegi et al. 1999; Gruppioni et al. 1999). At higher redshifts still, submillimetre sky surveys are already providing strong constraints (e.g. Hughes et al. 1998; Barger, Cowie & Richards 2000).

Finally, we note that Madau et al. (1998) could reproduce the  $K$ -band galaxy counts in an  $\Omega = 1$ ,  $\Lambda = 0$  cosmology. Our results are therefore suggestive of a non-zero  $\Lambda$ , as already suggested by many other recent approaches (see e.g. Peacock et al. 2001 and references therein).

## ACKNOWLEDGMENTS

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We would like to thank Andreas Efstathiou, Bob Mann and Michael Rowan-Robinson for stimulating discussions during this work, and the anonymous referee for helpful comments.

## REFERENCES

- Barger A., Cowie L. L., Sanders D. B., 1999a, *Apl*, 518, L5  
 Barger A., Cowie L. L., Smail I., Ivison R. J., Blain A. W., Kneib J.-P., 1999b, *AI*, 117, 2656  
 Barger A. J., Cowie L. L., Richards E. A., 2000, *AI*, 119, 2092  
 Baugh C. M., Cole S., Frenk C. S., Lacey C. G., 1998, *Apl*, 498, 504  
 Blain A. W., Smail I., Ivison R. J., Kneib J.-P., 1999a, *MNRAS*, 302, 632  
 Blain A. W., Smail I., Ivison R. J., Kneib J.-P., 1999b, *MNRAS*, 307, 480  
 Ciliegi P. et al., 1998, *MNRAS*, 302, 222  
 Condon J. J., 1987, *AJ*, 65, 485  
 Condon J. J., 1989, *Apl*, 338, 13  
 Condon J. J., 1992, *ARA&A*, 30, 575  
 Condon J. J., Yin Q. F., 1990, *Apl*, 357, 97  
 Condon J. J., Anderson M. L., Helou G., 1991, *Apl*, 376, 95  
 Cram L., Hopkins A., Mobasher B., Rowan-Robinson M., 1998, *Apl*, 507, 155  
 Devereux N. A., Eales S. A., 1989, *Apl*, 340, 708  
 Eales S., Lilly S., Gear W., Dunne L., Bond J. R., Hammer F., Le Fèvre O., Crampton D., 1999, *Apl*, 515, 518  
 Eales S., Lilly S., Webb T., Dunne L., Gear W., Clements D., Yun M., 2000, *AI*, 120, 2244  
 Gallego J., Zamorano J., Aragón-Salamanca A., Rego M., 1995, *Apl*, 455, L1  
 Gruppioni C. et al., 1999, *MNRAS*, 305, 297  
 Haarsma D. B., Partridge R. B., Windhorst R. A., Richards E. A., 2000, *Apl*, 544, 641  
 Heckman T. M., Carmelle R., Leitherer C., Garnett D. R., van der Rydt F., 1998, *Apl*, 503, 646  
 Ho L. C., Filippenko A. V., Sargent W. L. W., 1997, *AJ*, 112, 315  
 Hughes D., Serjeant S., Dunlop J., Rowan-Robinson M., Blain A., Mann R. G., Peacock J., Efstathiou A., Gear W., Oliver S., Lawrence A., Longair M., Goldschmidt P., Jemmes T., 1998, *Nature*, 394, 241  
 Ivison R. J., Smail I., Barger A. J., Kneib J.-P., Blain A. W., Owen F. N., Kerr T. H., Cowie L. L., 2000, *MNRAS*, 315, 209  
 Kennicutt R. C., 1983, *Apl*, 272, 54  
 Kroker H., Genzel R., Krabbe A., Tacconi-Garman L. E., Tecza M., Thatte N., 1996, *Apl*, 463, L55  
 Lemonon L., Pierre M., Cesarsky C. J., Elbaz D., Pello R., Soucail G., Vigroux L., 1998, *A&A*, 334, L21  
 Lilly S. J., Le Fèvre O., Hammer F., Crampton D., 1996, *Apl*, 460, L1  
 Lilly S. J., Eales S. A., Gear W. K. P., Hammer F., Le Fèvre O., Crampton D., Bond J. R., Dunne L., 1999a, *Apl*, 518, 641  
 Lilly S. J. et al., 1999b, in Carollo C. M., Ferguson H. C., Wyse R. F. G., eds, *The formation of galactic bulges*, Cambridge Univ. Press, Cambridge, p. 26  
 Madau P., Ferguson H. C., Dickinson M. E., Giavalisco M., Steidel C. C., Fruchter A., 1996, *MNRAS*, 283, 1388  
 Madau P., Porzetti L., Dickinson M., 1998, *Apl*, 498, 106  
 Meurer G., Heckman T., Leitherer M. D., Leitherer C., Lowenthal J., 1997, *AI*, 114, 54  
 Meurer G. R., Heckman T. M., Calzetti D., 1999, *Apl*, 521, 64  
 Oliver S., Gruppioni C., Serjeant S., 1998, *MNRAS*, submitted  
 Oliver S. et al., 2000, *MNRAS*, 316, 749  
 Peacock J. A., Dodds S. J., 1994, *MNRAS*, 267, 1020  
 Peacock J. A. et al., 2000, *MNRAS*, 318, 535  
 Peacock J. A. et al., 2001, *Nature*, 410, 169  
 Rowan-Robinson M. et al., 1997, *MNRAS*, 289, 490  
 Schmidt M., 1968, *Apl*, 151, 393  
 Serjeant S. et al., 1997, *MNRAS*, 289, 457  
 Serjeant S. et al., 2001, *MNRAS*, submitted  
 Steidel C. C., Adelberger K. L., Dickinson M., Giavalisco M., Pettini M., Kellogg M., 1998, *Apl*, 492, 428  
 Taniguchi Y. et al., 1997, *A&A*, 328, L9  
 Thomson H. A., Magewski S., Descartes L., Hereld M., 1990, *Apl*, 364, 456  
 Tresse L., Maddox S. J., 1998, *Apl*, 495, 691  
 Véron-Cetty M. P., Véron P., 1993, *ESO Scientific Report* 13

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.